Optimal Operation and Control of Thermal Energy Systems

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PhD Defence
I Optimal operation and control for steam cycles – plantwide perspective
Overview: Scope

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II Input transformations for linearization, decoupling and feedforward disturbance rejection
Overview: Scope

I. Optimal operation and control for steam cycles – plantwide perspective

II. Input transformations for linearization, decoupling and feedforward disturbance rejection

Industry nonlinear static model based calculation block, but little theory
Overview: Scope

I Optimal operation and control for steam cycles – plantwide perspective

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Industry: nonlinear static model based calculation block, but little theory

Academia: heavy mathematical treatment of linearizing nonlinear dynamic systems, but few applications
Overview: Scope

I Optimal operation and control for steam cycles – plantwide perspective

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Industry nonlinear static model based calculation block, but little theory

Academia heavy mathematical treatment of linearizing nonlinear dynamic systems, but few applications

III Handling constraints on manipulated used for inventory control to balance supply and demand
1. Overview: operation and control

- Scheduling (weeks)
- Site-wide Optimization (day)
- Local Optimization (hours)
- Supervisory Control (minutes)
- Regulatory Control (seconds)

Control layer

- CV$_1$s
- CV$_2$s

Process

Model predictive control or Advanced regulatory control

PID-control
1. Overview: thermal energy systems

\[ d_1 = q_S \]
\[ d_2 = q \]
\[ u_1 = q_D \]
\[ u_2 = q_{EP} \]
\[ v_h = q_{ST} \]
\[ u_3 = q_{TP} \]

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1. Overview: thermal energy systems
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\[ \begin{align*}
    d_2 &= T_0^0 \\
    d_3 &= F_2 \\
    w &= T_c \\
    p_0 &\text{ Boiler} \\
    T_H &\text{ Combustion} \\
    p_H &\text{ Flue gas} \\
    z_H &\text{ MV1} \\
    z_{HC} &\text{ MV2} \\
    T_L &\text{ Electric grid} \\
    p_L &\text{ Hot water storage tank} \\
    z_{LC1} &\text{ Charging} \\
    z_{LC2} &\text{ Discharging}
\end{align*} \]
2. Optimal operation and control of steam cycles

![Diagram of steam cycle]

- Boiler
- Condenser
- Turbine-Generator
- Pump
- Combustion
- Flue gas
- Superheated steam
- Fuel
- Air
- Water

- Scheduling (weeks)
- Site-wide Optimization (day)
- Local Optimization (hours)
- Supervisory Control (minutes)
- Regulatory Control (seconds)

I. Identify operational objectives (steady-state)
II. Analyze performance of different control strategies (dynamic)

Framework: plantwide control

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2. Optimal operation and control of steam cycles
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I. Identify operational objectives
(steady-state)
2. Optimal operation and control of steam cycles

I. Identify operational objectives (steady-state)

II. Analyze performance of different control strategies (dynamic)
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I. Identify operational objectives (steady-state)
II. Analyze performance of different control strategies (dynamic)

Framework: plantwide control
2. Optimal operation and control of steam cycles

Control objectives:

I Long time scale:
▶ achieve optimal economic operation

II Short time scale:
▶ grid frequency regulation
▶ stabilize the plant
▶ reject local disturbances

Operational objectives:

I Produce energy:
▶ electric power
▶ steam
▶ electric power and steam

II Process a given amount of by-product:
▶ waste gases
▶ biomass residues
2. Optimal operation and control of steam cycles

Control objectives:

I. Long time scale:
   - Optimize economic operation

II. Short time scale:
   - Grid frequency regulation
   - Stabilize the plant
   - Reject local disturbances

Operational objectives:

I. Produce energy:
   - Electric power
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Control objectives:

- **Long time scale:**
  - achieve optimal economic operation
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Operational objectives:
- Produce energy:
  - electric power
  - steam
  - electric power and steam
- Process a given amount of by-product:
  - waste gases
  - biomass residues
2. Optimal operation and control of steam cycles: steady-state analysis

Degrees of freedom
→ 2 after stabilizing the process and controlling the active constraints

MV1  Hot gas flow rate
MV2  Steam turbine valve

Steps on MV1 and MV2

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2. Optimal operation and control of steam cycles: dynamic analysis

Operation modes – industrial standards

**Floating pressure**

**Boiler Driven**

**Turbine driven**
2. Optimal operation and control of steam cycles: dynamic analysis

Operation modes – parallel control

Valve position control

\[ z_v^{sp} = 90\% \]

2 controllers: P and PI

\[ W^{sp} \]

\[ W \]

\[ W \]

\[ W \]

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2. Optimal operation and control of steam cycles: simulation results

CVs

MVs
3. Input transformations for linearization, decoupling and feedforward disturbance rejection

The main idea

\[ g^{-1}(v, w, y, d) \]

Controller \( C \) (dynamic)

Inverse input transformation (static)

Process (nonlinear)

Transformed system (linear)
3. Input transformations for linearization, decoupling and feedforward disturbance rejection

The main idea

What?

Why?

How?
3. Input transformations for linearization, decoupling and feedforward disturbance rejection

The main idea

What? Powerful and simple approach for control of nonlinear systems to achieve decoupling, linear response and disturbance rejection.

Why?

How?
3. Input transformations for linearization, decoupling and feedforward disturbance rejection

The main idea

What? Powerful and simple approach for control of nonlinear systems to achieve decoupling, linear response and disturbance rejection.

Why? Existing theories (e.g. feedback linearization) are (seemingly) very complex and not widely used in industrial settings.

How?
3. Input transformations for linearization, decoupling and feedforward disturbance rejection

The main idea

What? Powerful and simple approach for control of nonlinear systems to achieve decoupling, linear response and disturbance rejection.

Why? Existing theories (e.g. feedback linearization) are (seemingly) very complex and not widely used in industrial settings.

How? Simple manipulated variable (MV) transformations derived from nonlinear model equations.
3. Input transformations for linearization, decoupling and feedforward disturbance rejection

The main idea

Example: static process

Model: \( y = u - d \)

Transformed input: \( v = u - d \) \( \Rightarrow \) Transformed system: \( y = v \)

Find \( u: \quad u = v + d \), given \( v \) and \( d \).
3. Input transformations for linearization, decoupling and feedforward disturbance rejection

The main idea

Other examples:

\[ v = u + d \]
\[ v = \frac{u}{d} \]
\[ v = \frac{u_1}{u_2} \]
\[ v = u_1 - u_2 \]
\[ v = w \]
3. Input transformation

![Diagram showing the input transformation process]

- $y \in \mathbb{R}^{n_y}$ outputs
- $w \in \mathbb{R}^{n_w}$ additional measurements
- $u \in \mathbb{R}^{n_u}$ original inputs
- $y^s \in \mathbb{R}^{n_y}$ setpoint
- $d \in \mathbb{R}^{n_d}$ disturbances
- $v \in \mathbb{R}^{n_u}$ transformed inputs
3. Input transformation

\[ y \in \mathbb{R}^{n_y} \text{ outputs} \]
\[ w \in \mathbb{R}^{n_w} \text{ additional measurements} \]
\[ u \in \mathbb{R}^{n_u} \text{ original inputs} \]
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\[ d \in \mathbb{R}^{n_d} \text{ disturbances} \]
\[ v \in \mathbb{R}^{n_u} \text{ transformed inputs} \]

**Assumptions**

- *as many* outputs as inputs \((n_y = n_u)\)
- disturbances \((d)\) can be measured
- some variables \((w)\) can be measured (e.g. flows, or additional states)
3. Derivation of transformed inputs

\begin{align*}
\text{Model:} & \quad \frac{dy}{dt} = f(y, u, d) \\
\text{Model:} & \quad y = f_0(u, d)
\end{align*}

The transformed system is:

\begin{align*}
\text{Model:} & \quad \frac{dy}{dt} = Ay + Bv \\
\text{Model:} & \quad y = B_0 v_0
\end{align*}

First-order (dynamic case), linear, decoupled system and with no effect from disturbances.
3. Derivation of transformed inputs

Model: \[
\frac{dy}{dt} = f(y, u, d)
\]

\[
y = f_0(u, d)
\]
3. Derivation of transformed inputs

Model: \[ \frac{dy}{dt} = f(y, u, d) \]

Define the transformed input \((v)\) as:

\[ v_A = B^{-1}(f(y, u, d) - Ay) \]

\[ v_0 = B_0^{-1}f_0(u, d) \]
3. Derivation of transformed inputs

Dynamic Static

Model: \[ \frac{dy}{dt} = f(y, u, d) \]
\[ y = f_0(u, d) \]

Define the transformed input \((v)\) as:
\[ v_A = B^{-1} (f(y, u, d) - Ay) \]
\[ v_0 = B_0^{-1} f_0(u, d) \]

\(A, B\) \ and \(B_0\) are tuning parameters.
3. Derivation of transformed inputs

Dynamic

Static

Model: \( \frac{dy}{dt} = f(y, u, d) \)

\( y = f_0(u, d) \)

Define the transformed input (\( v \)) as:

\[ v_A = B^{-1} (f(y, u, d) - Ay) \]

\[ v_0 = B_0^{-1} f_0(u, d) \]

The transformed system is:

\[ \frac{dy}{dt} = Ay + Bv_A \]

\[ y = B_0 v_0 \]
3. Derivation of transformed inputs

Model: \[
\frac{dy}{dt} = f(y, u, d) \quad \text{and} \quad y = f_0(u, d)
\]

Define the transformed input \((v)\) as:
\[
v_A = B^{-1} \left( f(y, u, d) - Ay \right)
\]

The transformed system is:
\[
\frac{dy}{dt} = Ay + Bv_A \quad \text{and} \quad y = B_0 v_0
\]

First-order (dynamic case), linear, decoupled system and with no effect from disturbances.
Use of extra measurements

Model: \( \frac{dy}{dt} = f(y, u, w, d) \)

Transformed input \( v \): \( v_A = B_0^{-1}(f(y, u, w, d) - Ay) \)

Extra variables \( w \) that depend on \( u \)

- may replace measurements of disturbances
- may be used for unmodelled dynamics or uncertainties
- should be stable (i.e. no RHP-zeros).
Tuning parameters $A$ and $B$

Transformed input ($v$): $v_A = B^{-1} (f(y, u, w, d) - Ay)$

**How to select $A$?** ⇒ Design decision

1. $A = \text{diag} \left( \frac{\partial f(y, u, w, d)}{\partial y} \right)^*$, i.e. diagonal elements of the Jacobian
   ⇒ small positive feedback from $y$ to $v$ nominally

2. $B = \text{I keep } k_v y = k_u u \Rightarrow B = \text{diag}(\tilde{B}) = \text{diag}(\frac{\partial f(y, u, w, d)}{\partial u})^*$
Tuning parameters $A$ and $B$

Transformed input ($v$): $v_A = B^{-1} (f(y, u, w, d) - Ay)$

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   ⇒ small positive feedback from $y$ to $v$ nominally
2. larger $A$ to speed-up the response

How to select $B$?

1. $B = I$ keep $k_v y = k_u u$ ⇒ $B = \text{diag}(\tilde{B}) = \text{diag}(\frac{\partial f(y,u,w,d)}{\partial u})^*$
Tuning parameters $A$ and $B$

Transformed input ($v$): $v_A = B^{-1} (f(y, u, w, d) - Ay)$

How to select $A$? $\Rightarrow$ Design decision

1. $A = \text{diag} \left( \left. \frac{\partial f(y,u,w,d)}{\partial y} \right|^{\star} \right)$, i.e. diagonal elements of the Jacobian
   $\Rightarrow$ small positive feedback from $y$ to $v$ nominally

2. larger $A$ to speed-up the response

3. smaller $A$ to slow-down the response

4. $A = 0$ for integrating processes, e.g., level control (i.e., similarly to feedback linearization methods).

How to select $B$? $\Rightarrow$ Design decision

- $B = I$ keep $k_v y = k_u u$ $\Rightarrow$ $B = \text{diag} (\tilde{B}) = \text{diag} \left( \left. \frac{\partial f(y,u,w,d)}{\partial u} \right|^{\star} \right)$
Tuning parameters $A$ and $B$

Transformed input ($v$): $v_A = B^{-1} (f(y, u, w, d) - Ay)$

**How to select $A$?** ⇒ **Design decision**

1. $A = \text{diag} \left( \left. \frac{\partial f(y, u, w, d)}{\partial y} \right|_* \right)$, i.e. diagonal elements of the Jacobian
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How to select $A$? $\Rightarrow$ Design decision

1. $A = \text{diag} \left( \left. \frac{\partial f(y, u, w, d)}{\partial y} \right|^{*} \right)$, i.e. diagonal elements of the Jacobian $\Rightarrow$ small positive feedback from $y$ to $v$ nominally
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3. smaller $A$ to slow-down the response
4. $A = 0$ for integrating processes, e.g., level control (i.e., similarly to feedback linearization methods).

How to select $B$? $\Rightarrow$ Design decision

- $B = I$
- keep $k_{vy} = k_{uy} \Rightarrow B = \text{diag}(\tilde{B}) = \text{diag} \left( \left. \frac{\partial f(y, u, w, d)}{\partial u} \right|^{*} \right)$
- $B = -A$
Implementation of transformed inputs

Solves $v = f(y, u, w, d) - Ay$ w.r.t $u$, given $v, y, d$, and in some cases $w$.
Nonlinear feedforward controller
Implementation of transformed inputs

Solves $\nu = f(y, u, w, d) - Ay$ w.r.t $u$, given $\nu, y, d$, and in some cases $w$. Nonlinear feedforward controller

Implementations

- exact model based inversion $\Rightarrow$ explicit solution $u = g^{-1}y, \nu, w, d$
Implementation of transformed inputs

Solves $v = f(y, u, w, d) - Ay$ w.r.t $u$, given $v, y, d$, and in some cases $w$.

Nonlinear feedforward controller

Implementations

- exact model based inversion $\Rightarrow$ explicit solution $u = g^{-1}y, v, w, d$
- feedback based using an I-controller (cascade).

![Diagram of control system]

Controller $C$ (dynamic)

Inverse input transformation (static)

Process (nonlinear)

Transformed system (linear)
Feedback based implementation

Advantages

- safer implementation ⇒ does not invert the input transformation eq. to solve for $u$
- handles ⇒ RHP-zeros, measurement delays, plant-model mismatch
- more robust

Drawback

- does not give perfect disturbance rejection
Linear controller

- perfect model and measurements ⇒ do not need the outer feedback loop because the transformation ⇒ nonlinear feedforward controller

$$g^{-1}(v, w, y, d)$$
Inverse input transformation (static)

Process (nonlinear)
Linear controller

- perfect model and measurements ⇒ do not need the outer feedback loop because the transformation ⇒ nonlinear feedforward controller
- setpoint changes can be handled by directly changing $v^s$

$$g^{-1}(v, w, y, d)$$

Inverse input transformation (static)

Transformed system (linear)

$$\tau = -1/A$$
Linear controller

- perfect model and measurements $\Rightarrow$ do not need the outer feedback loop because the transformation $\Rightarrow$ nonlinear feedforward controller
- setpoint changes can be handled by directly changing $v^s$
- real plant $\Rightarrow$ unmeasured disturbances and unmodelled dynamics $\Rightarrow$ use decentralized SISO controllers for controlling $y$ using $v$ as inputs.
Example: control of heat exchanger hot outlet temperature

MVs (original inputs):
\[ u = F_c \text{ [kg/s]} \]

CVs (outputs):
\[ y = T_h \text{ [°C]} \]

DVs (disturbances):
\[ d_1 = T_c^0 \text{ [°C]} \]
\[ d_2 = T_h^0 \text{ [°C]} \]
\[ d_3 = F_h \text{ [kg/s]} \]
\[ d_4 = UA \text{ (unmeasured)} \]

w -variables:
\[ w = T_c \text{ [°C]} \]
Example: control of heat exchanger hot outlet temperature

Objective: find transformed input \((v_0)\) \(\Rightarrow\) disturbance rejection.
Example: control of heat exchanger hot outlet temperature

Objective: find transformed input ($v_0$) \Rightarrow disturbance rejection.

Static energy balance using $\epsilon - NTU$

$$y = T_h = (1 - \epsilon_h) T_h^{\text{in}} + \epsilon_h T_c^{\text{in}}$$

with $\epsilon_h = \epsilon_h(u, d_1, d_2, d_3)$
Example: control of heat exchanger hot outlet temperature

**Objective:** find transformed input \((v_0) \Rightarrow \) disturbance rejection.

Static energy balance using \(\epsilon - NTU\)

\[
y = T_h = (1 - \epsilon_h) T_{h}^{in} + \epsilon_h T_{c}^{in}
\]

with \(\epsilon_h = \epsilon_h(u, d_1, d_2, d_3)\)

Static energy balance using \(w\)– measurements \((T_c)\)

\[
y = T_h = T_{h}^{0} + \frac{F_c c_p}{F_h c_p} (T_{c}^{0} - T_c)
\]

Transformed system:

\[
y = v_0 \quad \text{or} \quad y = v_0, w
\]

Tuning parameter:

\[
B_0 = I
\]

Actual process is dynamic, but we use an input transformation derived from a static model.
Example: control of heat exchanger hot outlet temperature

Objective: find transformed input \((v_0)\) \(\Rightarrow\) disturbance rejection.

Static energy balance using \(\epsilon - NTU\)

\[
y = T_h = (1 - \epsilon_h) T_h^{in} + \epsilon_h T_c^{in}
\]

with \(\epsilon_h = \epsilon_h(u, d_1, d_2, d_3)\)

Static energy balance using \(w\)– measurements \((T_c)\)

\[
y = T_h = T_h^0 + \frac{F_c c_p_c}{F_h c_p_h} (T_c^0 - T_c)
\]

Transformed system: \(y = v_0\) or \(y = v_{0,w}\)

Tuning parameter: \(B_0 = I\)

Actual process is dynamic, but we use an input transformation derived from a static model
Example: control of heat exchanger hot outlet temperature. Open loop responses

Feedback-based implementation without the outer controller

Step response from \( v \) to \( y \)
Example: control of heat exchanger hot outlet temperature. Open loop responses

Feedback-based implementation without the outer controller

Step response from $v$ to $y$

Step response from $u$ to $v$
Example: control of heat exchanger hot outlet temperature. Closed loop responses
Handling constraints on manipulated variables (MV) used to balance supply and demand

\[ u_1, u_2, u_3, u_4, u_5 \] and \[ d_1, d_2 \] are variables representing supply and demand.

\[ MV_s := \text{adjustable supply} \]
\[ MV_d := \text{flexible demand} \]

Inventory \( m \): measure of demand-supply balance

Control objective: design decentralized control structure that sets the values of \( MV_s \) and \( MV_d \) to control \( m \)

Use \( MV_s \) when \( d_2 > d_1 \) Use \( MV_d \) when \( d_1 > d_2 \)
Handling constraints on (MVs) used to balance supply and demand

How to handle MV saturation?

\[ MV_s = MV_s^{\text{max}} \Rightarrow \text{use } MV_d \]
Handling constraints on (MVs) used to balance supply and demand

**How to handle MV saturation?**

\[ \text{MV}_s = \text{MV}_s^{\text{max}} \Rightarrow \text{use } \text{MV}_d \]

**Implementation:**
- split-range control

![Diagram of split-range control](image_url)
Handling constraints on (MV) used to balance supply and demand

How to handle MV saturation?

$MV_s = MV_{s}^{\text{max}} \Rightarrow$ use $MV_d$

Implementation:
- split-range control
- controllers with different setpoints

\[ y_{s1}^s + \Delta y = y_{s2}^s = y_{s1}^s + \Delta y \]

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Handling constraints on (MV)s used to balance supply and demand

How to handle MV saturation?

\[ \text{MV}_s = \text{MV}_s^{\text{max}} \Rightarrow \text{use } \text{MV}_d \text{ Implementation:} \]

- split-range control
- controllers with different setpoints
- selectors

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Bidirectional inventory control with optimal use of storage

TPM = $F^s$

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Bidirectional inventory control with optimal use of storage

TPM = $F^s$

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Bidirectional inventory control with optimal use of storage

\[ TPM = F^s \]
Bidirectional inventory control with optimal use of storage
Conclusion

Optimal operation and control of heat to power cycles

- steady-state and dynamic analysis

Handling MVs saturation for balancing supply and demand

MV-MV switching: split-range control, controllers with different setpoints

CV-CV switching: selectors

Bidirectional inventory control with high and low setpoints for each inventory gives optimal buffer storage management
Conclusion

Optimal operation and control of heat to power cycles

- steady-state and dynamic analysis
- turbine drive is faster, floating pressure has minimal throttling losses
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- control structures with embedded knowledge through input and output transformations
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Optimal operation and control of heat to power cycles
- steady-state and dynamic analysis
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Transformed inputs
- control structures with embedded knowledge through input and output transformations
- resulting transformed system from $v$ to $y \Rightarrow$ linear, independent of disturbances, decoupled
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Handling MVs saturation for balancing supply and demand

- MV-MV switching: split-range control, controllers with different setpoints
- CV-CV switching: selectors
- bidirectional inventory control with high and low setpoints for each inventory bin, optimal buffer storage management